RE-ORDER NO. 63-28

26 p

N64-20743
CAT. 13 Code 1
NASA CR 56178

SELECTION OF A TEMPERATURE CONTROL SYSTEM FOR A MARS PROBE

by

CLARK V. DOHNER

OTS PRICE

XEROX $ 2.60 ph

MICROFILM $ ______

January 10, 1963

Contract 950226

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

GENERAL ELECTRIC
RE-ENTRY SYSTEMS DEPARTMENT
A Department Of The Missile and Space Division
3198 Chestnut Street, Philadelphia 4, Penna.

SELECTION OF A TEMPERATURE CONTROL SYSTEM FOR A MARS PROBE

INTRODUCTION:

This paper presents the thermal design study for a Mars-probe entry vehicle - - Four types of temperature control systems are considered:

1) α/ϵ coating with solar cells
2) α/ϵ control
3) superinsulation with solar cells
4) radioisotope heat generation

The purpose of this paper is to show how the selection of a system should be approached by considering the analyses of several systems. Then, on the basis of a comparison of these systems, the ones which appear to be the most desirable are selected for further consideration.

DISCUSSION:

I. General System Requirements

Certain problem areas exist with any of the systems to be considered. The capsule must be held within a certain temperature range so that the electronic components will operate satisfactorily. Shield temperature must be maintained above a certain minimum; and the gradient around the shield must be prevented from exceeding a certain value, or else excessive thermal stresses will be encountered. Since the vehicle's battery is adversely affected by temperature extremes, it, too, must be maintained within specified temperature limits. During entry into the Martian atmosphere the capsule must be maintained within temperature limits until impact with the surface of Mars. All these problem areas must be considered when analyzing the various temperature control systems.

The general Mars-probe entry vehicle configuration is presented in Figure 1. This probe vehicle is attached to the "space bus", whose mission it is to fly-by Mars while the probe enters the Martian atmosphere. The probe remains attached to and in the shade of the space bus until separation of the two occurs. Separation may occur anywhere from 18 hours to 180 days prior to entry at Mars. However, the case for which the probe "sees" the greatest variation in environmental temperature (i.e., solar flux) occurs for separation at 180 days prior to entry (i.e., 180 day free-flight duration). The solar flux, for this case, varies from 406 BTU/hr-ft^2 (at separation) to 184 BTU/hr-ft^2 (at Mars).

During the transit phase of flight, the following temperature restrictions are imposed upon the probe:

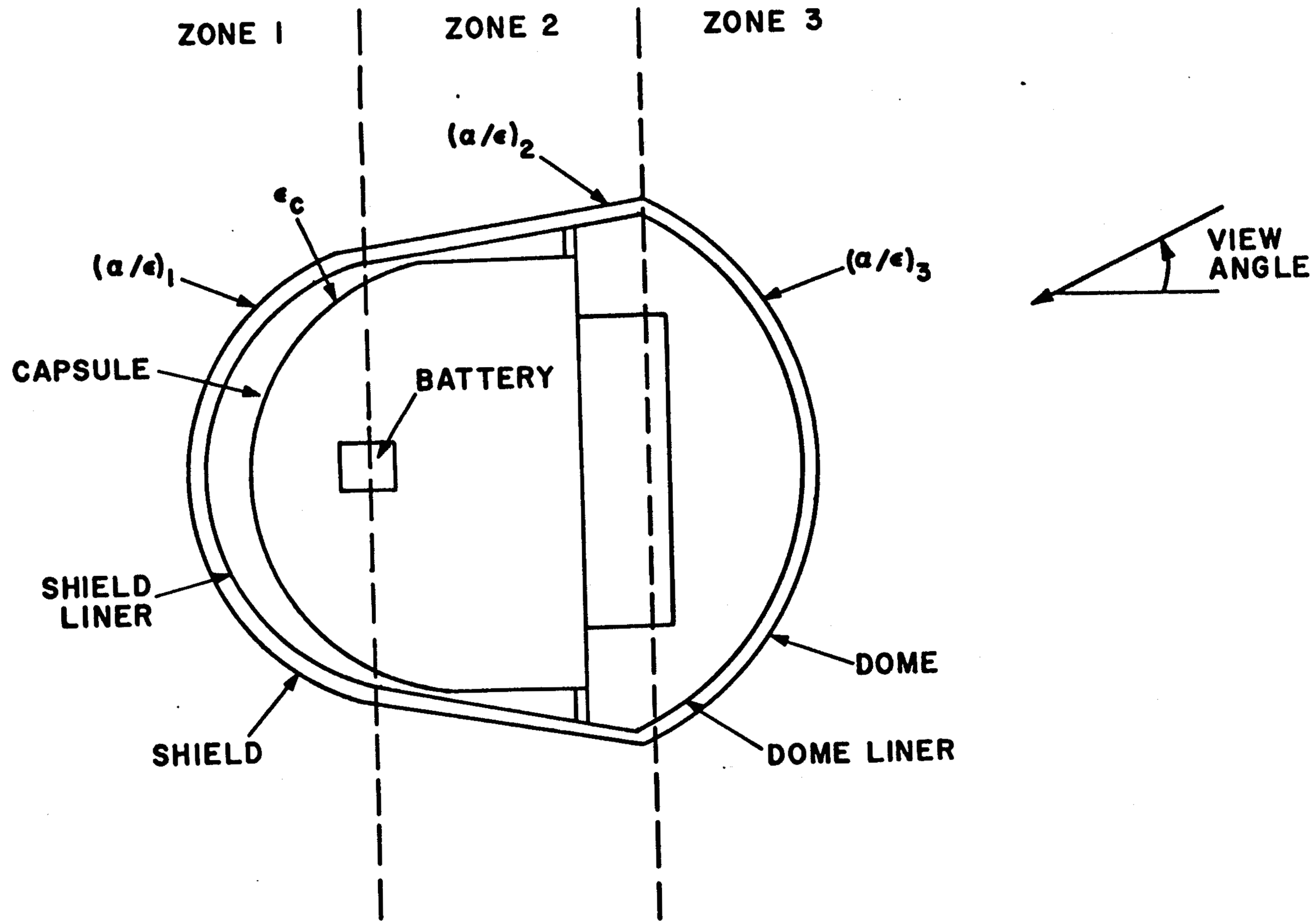

Figure 1. Vehicle Configuration

$$14^{\circ}F \le T_C \le 160^{\circ}F$$

$$50^{\circ}F \le T_B \le 100^{\circ}F \text{ (battery activated)}$$

$$-20^{\circ}F \le T_B \le 100^{\circ}F \text{ (battery unactivated)}$$

$$T_{S_{MIN.}} \ge -150^{\circ}F \ (310^{\circ}R)$$

$$T_{S_{MAX.}} - T_{S_{MIN.}} \le 300^{\circ}F \text{ (gradient around shield)}$$

where:

subscript C refers to capsule

subscript B refers to battery

subscript S refers to ablation re-entry heat shield

II. α/ϵ Coating System

This is a system of temperature control which makes use of coatings on the shield and capsule to limit the change in temperature of the capsule as the solar flux varies during the journey from earth to Mars. The basic system concept employed here is to allow the capsule to first heat up and then cool down as free flight time elapses (vehicle separated from space bus); but in so doing, to maintain the capsule temperature in the range 14°F to 160°F and the battery temperature in the range 50°F to 100°F.

A. Capsule Temperature

Required capsule coating values of α and ϵ are determined essentially by the free-flight phase of the vehicle's journey between earth and Mars (i.e., period between separation from bus and entry to Mars). Consider the transient temperature of the capsule as described by:

$$wC_p \frac{dT_C}{d\theta} = \alpha_e A_P S - \epsilon_e A_T \sigma T_C^4 + Q_g \tag{1}$$

and

$$\alpha_e = \frac{\alpha}{\epsilon} \epsilon_e \tag{2}$$

where

w = vehicle weight

C_p = specific heat capacity of vehicle

T_C = capsule temperature

α_e = effective value of solar absorptivity (based on capsule and sink temperatures)

A_p = projected area of vehicle

S = solar flux per unit area

ϵ_e = effective emissivity

A_T = total vehicle surface area

σ = Stefan-Boltzmann constant

Q_g = internal heat generation

α = solar absorptivity of exterior of vehicle

ϵ = emissivity of exterior of vehicle

The General Electric Matrix Heat Transfer Program was run on the IBM-7090 computer for obtaining solutions to the above equations. From the results of this run, Figure 2 was drawn.

Stable emissivities below approximately .02 are obtainable by the use of superinsulation. However, since the design concept presented here makes use of coatings rather than superinsulation, an effective emissivity of approximately .03-.04 will be used as a practical lower limit. For these values of effective emissivity, it may be seen from Figure 2 that the capsule temperature follows the sink temperature closely. [Sink temperature is defined by equation (1) when $\frac{dT_C}{d\theta} = 0$.]

Since orientation of the vehicle with respect to the sun may be arbitrary and since A_P is a function of orientation, it is necessary to achieve a fairly constant value of $\alpha_e A_P$ by the use of different coatings on different body parts (or nodes). This would then mean that the variation in the term $\alpha_e A_P S$ of equation (1) would be due principally to the variation in S. It may be found that the three nodes (or zones) of the vehicle can be coated to give the following values:

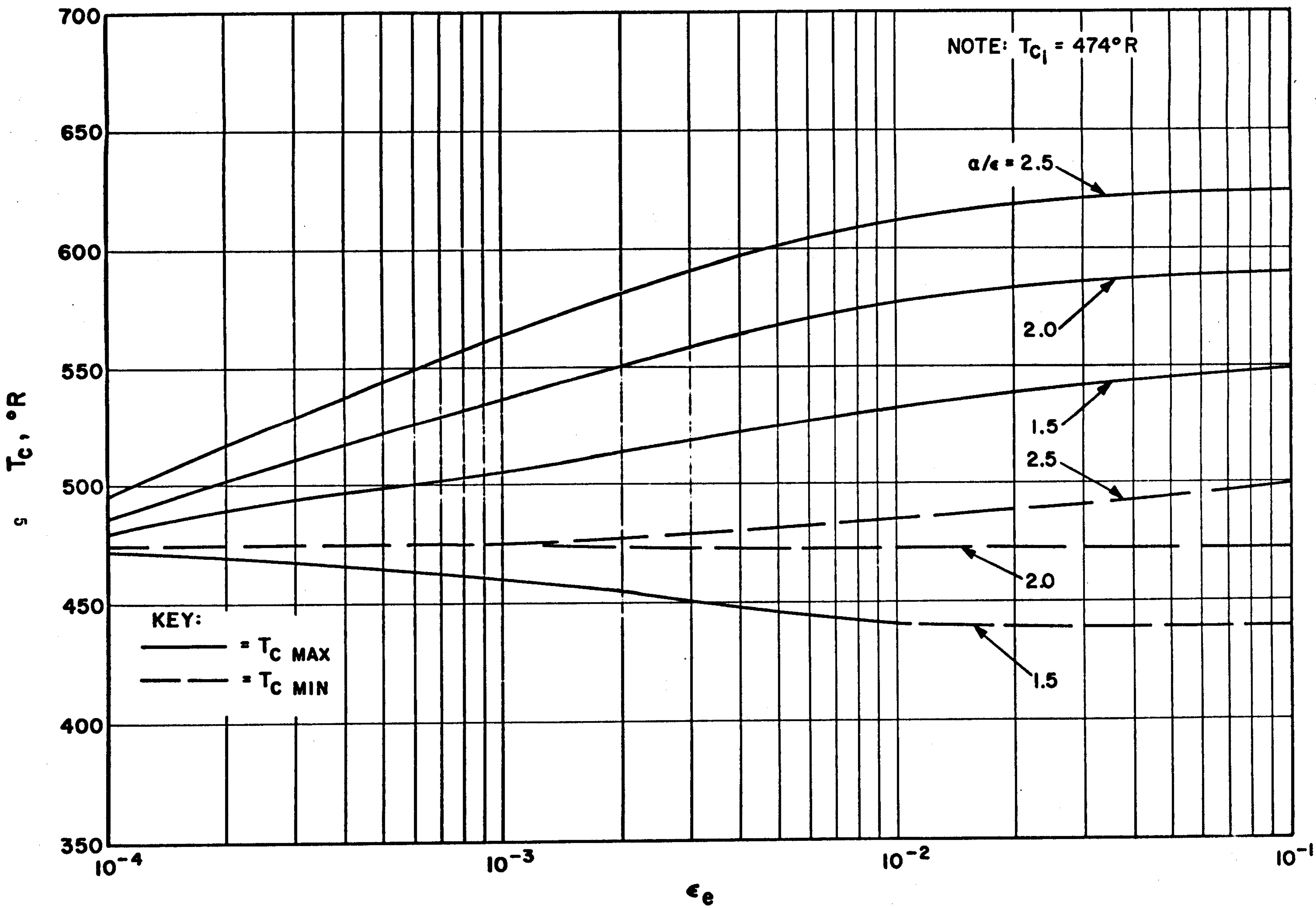

Figure 2. **Capsule Temperature Versus ϵ_e**

$$\left(\frac{\alpha}{\epsilon}\right)_1 = 2.46$$

$$\left(\frac{\alpha}{\epsilon}\right)_2 = 1.86$$

$$\left(\frac{\alpha}{\epsilon}\right)_3 = 2.32$$

With a tolerance of ± 5% for these coatings, the capsule temperature can vary from 14°F at separation from the space bus to 160°F at entry to Mars. The α/ϵ values for these coatings can be obtained by using a platinum, rhodium, or tantalum coating on the outside of the vehicle along with patches of black paint over some portions of the coating.

B. Shield Temperature

1. Shield Gradient

Since the maximum allowable shield temperature gradient is 300°F, a magnesium liner is required to maintain the gradient at this value or below since the shield ablation material has a low thermal conductivity.

Figure 3 is derived from the analysis of Reference 1 and presents the maximum and minimum shield temperatures occurring when the solar flux equals 406 BTU/hr.-ft.^{2} (at time of separation of vehicle from space bus). These curves neglect internal radiation and are, therefore,conservative.

For $\alpha/\epsilon = 2.5$ and $T_{S_{MAX.}} - T_{S_{MIN.}} = 300^\circ R$, it may be seen from Figure 3 that $(kt)/\epsilon = 1$. This means that a .02 inch thick magnesium liner may be used to limit the maximum thermal gradient to 300°R.

2. Minimum Shield Temperature

The case for which the shield temperature reaches a minimum may be evidenced when the vehicle is in the shade of the space bus. For a capsule emissivity of .03 to .04 and a shield inner emissivity of .9, the outer shield emissivity (outside of vehicle) may be equal to .1. This will prevent the shield temperature from falling below -150°F.

C. Battery Configuration

The allowable temperature range for the battery is 50°F to 100°F for an activated battery, or -20°F to 100°F for an unactivated battery which is to be

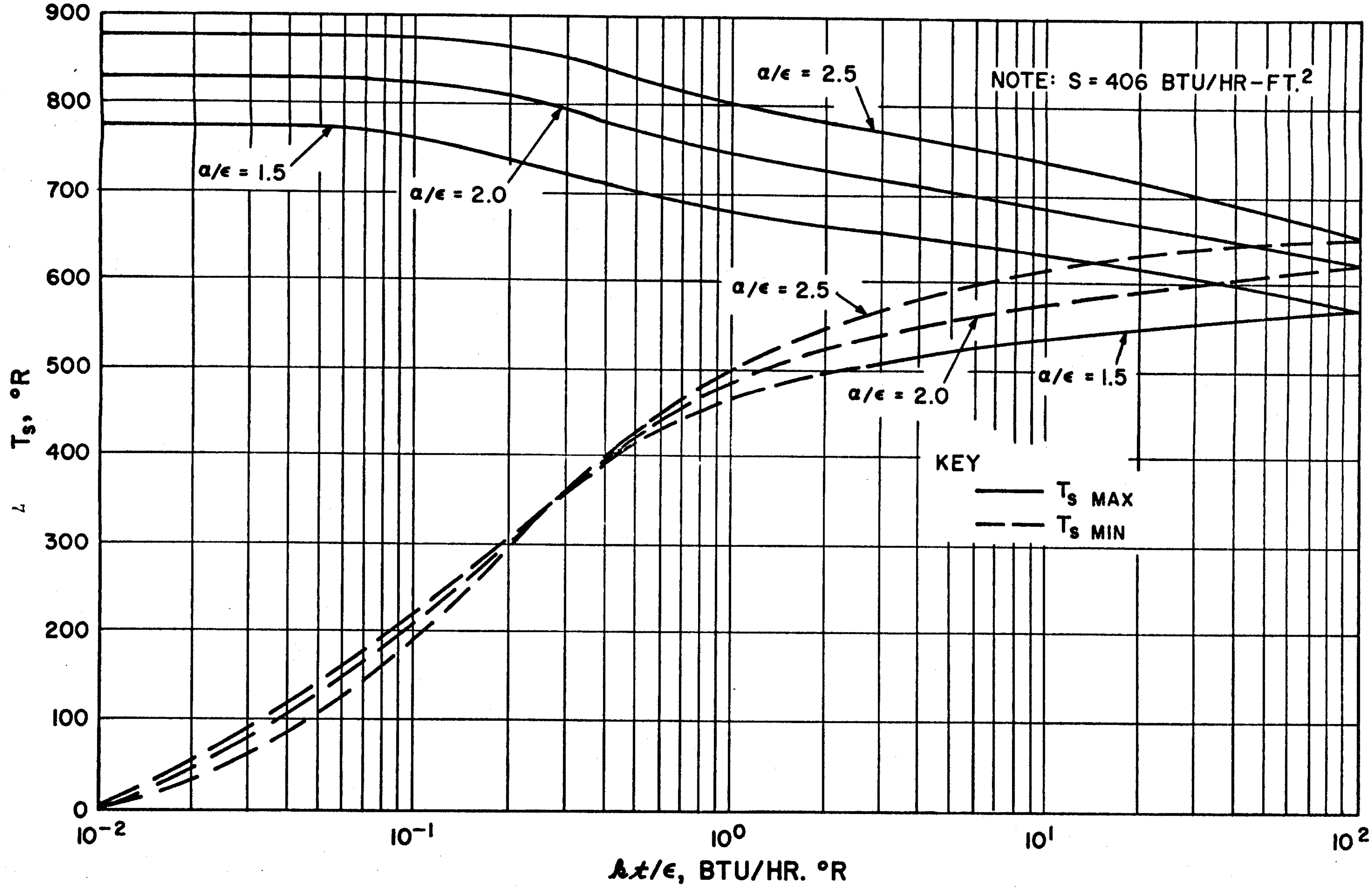

Figure 3. Shield Temperature Versus (kt/ϵ)

chemically activated at a predetermined time after separation of the vehicle from the space bus. Since the latter case would require heating the battery up to 50°F after activation, it would impose as much of a problem as would the former case. Battery temperature, therefore,could be maintained between 50°F and 100°F. Figure 4 shows a typical thermal configuration for the battery.

To maintain the battery temperature under 100°F, thermal isolation of the battery from the capsule would be employed. This is accomplished by the use of nylon strands to support the battery from its corners along with the use of a low effective emissivity insulation (superinsulation) around the battery. A heat of fusion material (eicosane) is necessary to accept the heat which would otherwise be absorbed by the battery when the capsule temperature exceeds 100°F. The weight of eicosane (melts at 100°F and absorbs approximately 100 BTU/lb. of system) required would be 6.5 lb. This weight could be reduced if a water vaporization system similar to the one used on the bio-medical packages of the Discoverer were used instead of the eicosane. The water vaporization system would have a heat absorbing capacity of 500 BTU/lb. of system. Hence, it would weigh only one-fifth as much as the eicosane - namely 1.3 lb.

To maintain the battery temperature above 50°F, thermostatically-controlled heaters could be used, with a control point of approximately 80°F. Heater power would be generated by solar cells attached to the outside of the vehicle.

A frangible disc, set to break at 5 psi pressure difference, can be used in the shell around the battery to keep the system free from contamination prior to launch.

D. Heater Power Supply

Due to the long time duration for which heater power will be required to maintain battery temperature, solar power appears to be best. The low power dissipation ($\approx$ 1 watt) indicates that photovoltaic cells are ideally suited for the mission.

Random orientation of the vehicle during transit dictates that patches of cells must be placed over the vehicle so that some cells can always supply sufficient power to operate the heaters. Since the output of each patch, or grouping of cells, is limited to approximately the output of the least exposed cell in the patch, the patches must be connected in parallel, rather than in series, so an unilluminated patch does not act as a load for an illuminated patch.

Figure 5 shows the logical locations for solar cell patches. A power system optimization with respect to patch sizes and number of patches indicates that the 4-patch circumferential arrangement shown in Figure 5 is best for this case; it keeps the number of heaters and thermostats to a minimum and yet is adequate to maintain the one watt power required for maintaining the battery temperature. A five-patch system would provide redundancy in case of the failure of one patch, if the patches themselves cannot be made redundant.

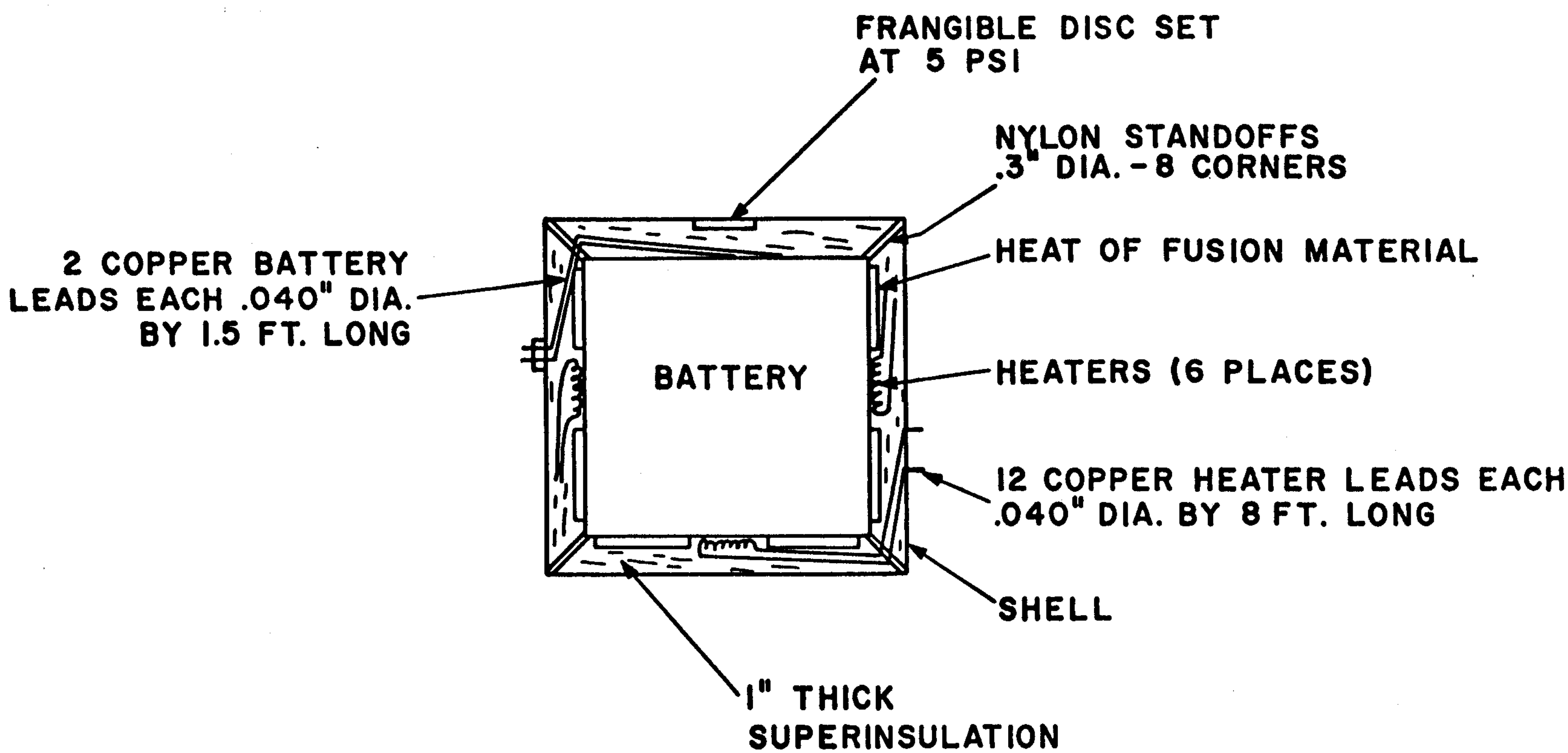

Figure 4. Battery Configuration

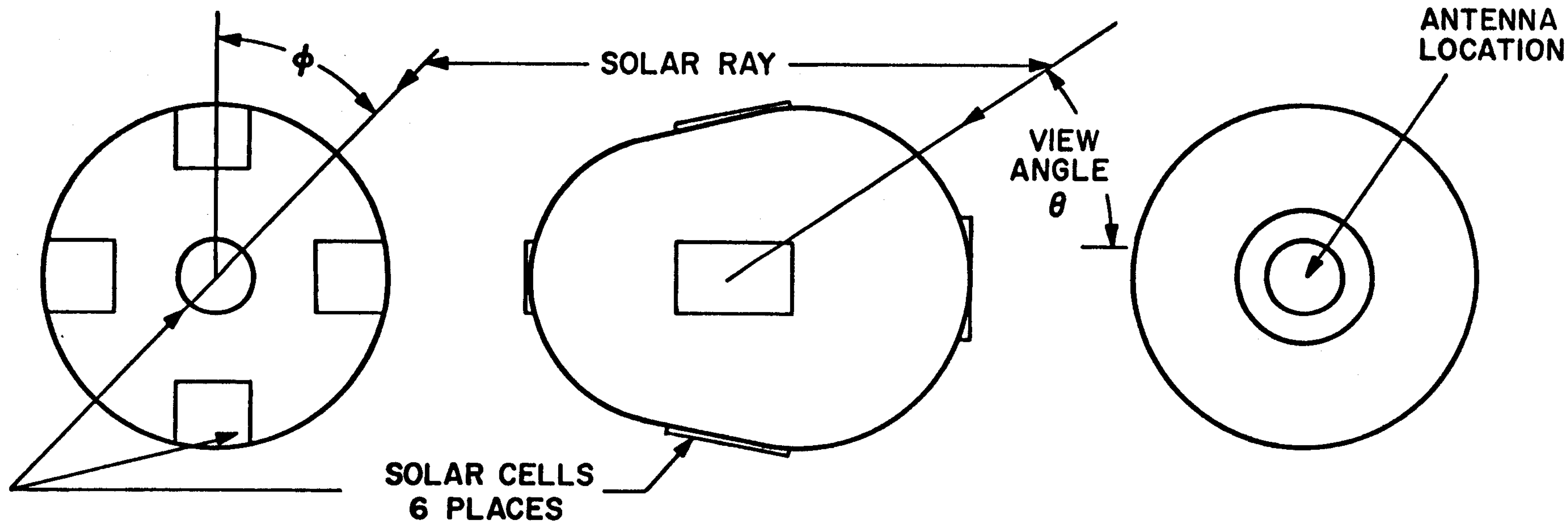

Figure 5. Solar Cell Configuration

Power output of the entire solar cell system as a function of view angle (θ) is shown in Figure 6. For this figure, the angle ϕ was chosen to minimize the output.

E. Heating Requirements while on Space Bus

In order to maintain the capsule minimum temperature of 14°F and the battery minimum temperature of 50°F while the vehicle is attached to and in the shade of the space bus, it may be calculated that 26 watts are required for heating the capsule and 1 watt is necessary for heating the battery.

F. Capsule Temperature during Entry at Mars

During entry at Mars, the capsule may become too cold unless a one inch thick layer of fiberglas insulation is used. This fiberglas insulation blanket would be placed on the inside of the capsule and would weigh approximately 3 lbs.

III. α/ϵ Control System

This type of system would require the placement of a magnesium "clam-shell" around the outside of the vehicle. Copper tubing filled with a liquid Freon or Propane then would be wound around the outside of this clam-shell and in intimate thermal contact with it. Contraction or expansion of the liquid due to temperature changes would actuate open-closed type shutters (no intermediate positions, only full-open or full-closed) to increase or decrease the α/ϵ value so that an average vehicle temperature of approximately 80°F would be maintained.

Open-closed type shutters are necessary for this system rather than proportional control type of shutters because of varying solar flux received by the vehicle during free flight. Varying flux means that the value of α/ϵ necessary to maintain an average temperature of 80°F at the beginning of free flight will be different from the value needed to maintain the same temperature at Mars. The lowest value of α/ϵ which is needed to maintain an average temperature of 80°F is approximately equal to 1.39 and occurs at the beginning of free flight (with maximum projected area). The highest value of α/ϵ needed to maintain the same average temperature is approximately 3.44 and occurs at Mars (with minimum projected area).

Solar cells and heat of fusion material would not be needed for temperature control if this system were used, since the temperature of the entire vehicle would be maintained around 80°F, which is well within the temperature limitations imposed upon the battery.

The clam-shell and shutters must be ejected from around the vehicle prior to parachute deployment at Mars. This is a disadvantage in the respect that an ejection system would be required; however, it is an advantage in the respect that the weight of the clam-shell, shutters, and tubing will not add to the entry weight of the vehicle.

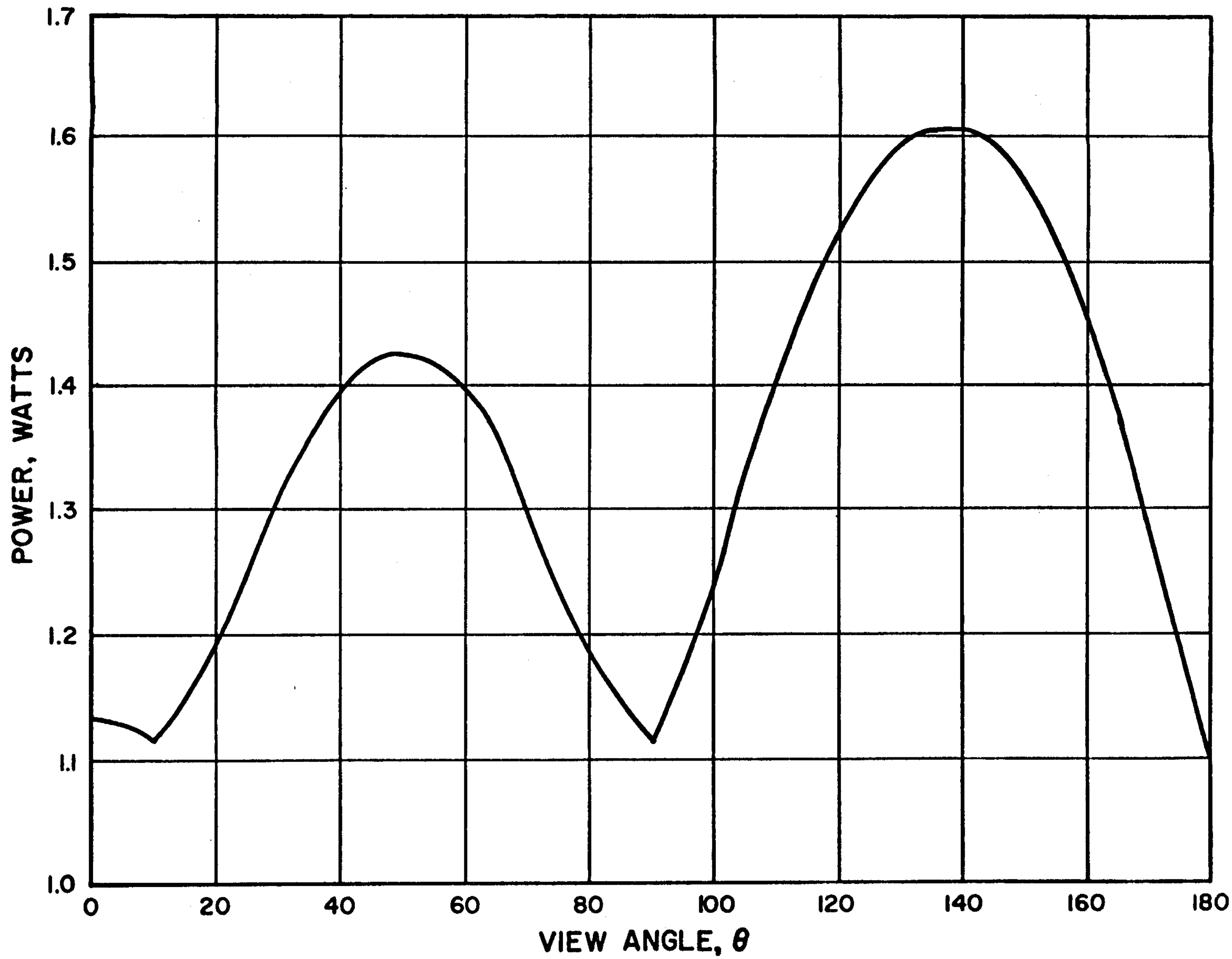

Figure 6. Solar Cell Power Output At Mars

The reliability of such a system must be considered. This system uses mechanical control to vary α/ϵ and to eject the clam-shell and shutters. Reliabilities of these machanical systems must be compared with the thermal reliabilities of the other types of systems considered.

IV. Superinsulation System with Solar Cells

This system consists of superinsulation wrapped around the outside of the vehicle with solar cells affixed to it. The superinsulation would minimize the effects due to the variation in solar flux and also maintain the shield temperature at that of the capsule (hence reducing shield thermal gradients). Solar cells would maintain the capsule temperature above the required minimum.

A. Variation in Effective Emissivity

The effective emissivity of a superinsulation (i.e., multiple-radiation-barrier type insulation) may vary by a factor of 10:1 from one end of the vehicle to another. This is due to one or more of the following reasons:

1) Method of attachment to vehicle
2) Local variation in foil emissivity
3) Random contact between foils

The approach to this problem may be made in terms of $\left(\frac{A_P}{A_T}\right)_e$, where:

$$\left(\frac{A_P}{A_T}\right)_e = \frac{A_{S,P} + \frac{\mathcal{F}B}{\mathcal{F}S} A_{B,P} + \frac{\mathcal{F}H}{\mathcal{F}S} A_{H,P}}{A_S + \frac{\mathcal{F}B}{\mathcal{F}S} A_B + \frac{\mathcal{F}H}{\mathcal{F}S} A_H}$$

Subscripts:

P - refers to projected value of area
T - refers to total value of area
S - refers to shield
B - refers to back end (domed end) of vehicle
H - refers to holes in the insulation or attachment points to the vehicle

Figure 7 is then constructed with $\frac{\mathcal{F}B}{\mathcal{F}S} = \frac{\epsilon_B}{\epsilon_S} = 10$ or .1 for various cases of $\frac{\mathcal{F}H}{\mathcal{F}S} = \frac{\epsilon_H}{\epsilon_S}$. Thus, it may be seen that $\frac{A_P}{A_{T_e}}$ can vary from .04 to .8.

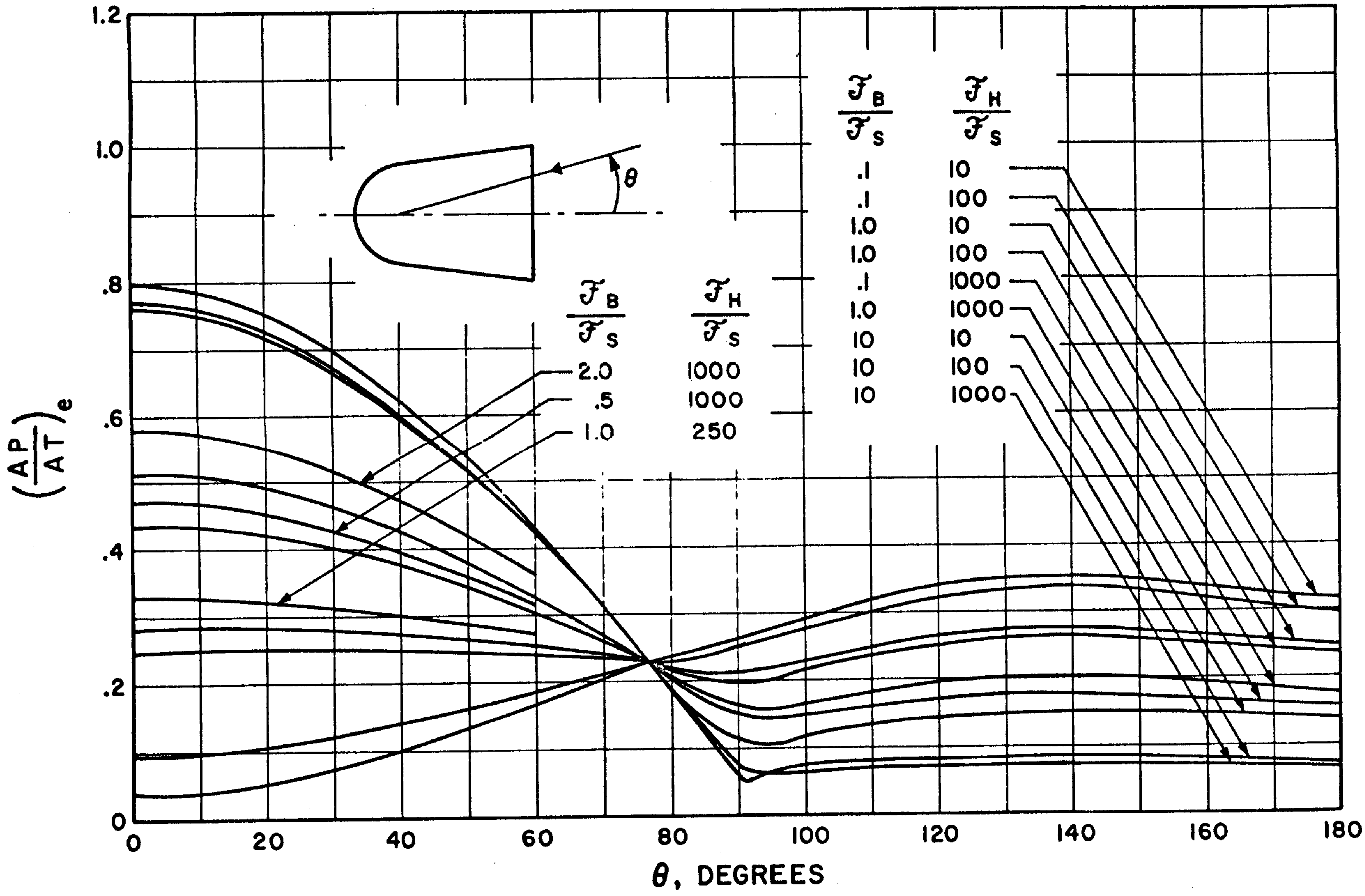

Figure 7. Variation of $\left(\frac{A_P}{A_T}\right)_e$ With View Angle

B. Design Selection

The design selection for this system may be made by considering the sink temperature, T_W:

$$\sigma T_{W_{MAX.}}^{4} = \left(\frac{\alpha}{\epsilon}\right)\left(\frac{A_P}{A_T}\right)_{e_{MAX.}} S_{MAX.} + \frac{Q_g \text{ (watts) } 3.413}{\epsilon_{e_{MIN.}} A_T} \quad (3)$$

$$\sigma T_{W_{MIN.}}^{4} = \left(\frac{\alpha}{\epsilon}\right)\left(\frac{A_P}{A_T}\right)_{e_{MIN.}} S_{MIN.} + \frac{Q_g \text{ (watts) } 3.413}{\epsilon_{e_{MIN.}} A_T} \quad (4)$$

where

$$\left(\frac{A_P}{A_T}\right)_{e_{MAX.}} = .8\ ; \quad \left(\frac{A_P}{A_T}\right)_{e_{MIN.}} = .04$$

$$S_{MAX.} = 406 \frac{BTU}{hr\text{-}ft^2}\ ; \quad S_{MIN.} = 184 \frac{BTU}{hr\text{-}ft^2}$$

$\epsilon_{e_{MAX.}} = .00308$; $\epsilon_{e_{MIN.}} = .000308$ for one inch of superinsulation

$A_T = 25\ ft^2$.

From these values it can be shown that by selecting $\alpha/\epsilon = .5$:

$T_{W_{MAX.}} = 95^{o}F$ using $Q_g = 0$ watts

$T_{W_{MIN.}} = 50^{o}F$ using $Q_g = 2.54$ watts

The required solar cells to produce 2.54 watts would weigh 1.62 lb. and would be attached in the locations shown by Figure 5. The one inch thickness of superinsulation would weigh 9.8 lb.

V. Radioisotope Heat Generation System

Capsule temperature may be controlled through the use of a radioisotope thermoelectric generator (RTG) unit which could be mounted either inside the capsule or outside the vehicle. The RTG unit would be desirable in the respect that it would provide a source of electrical power for recharging the vehicle's battery.

The underlying ideas in using an RTG for temperature control are:

1) Minimization of the effect that the variation in solar flux has on capsule temperature.

2) Provision of a source of heat to maintain capsule temperature requirements when vehicle is in shade of bus.

Due to the scalability of the RTG unit (i.e., 2.7 to 25 electrical watts), all sizes can be considered. However, because of the relatively low efficiency of the thermoelectric elements (5%), the thermal dissipation is twenty times the electrical power output. For this reason, the larger units need to be used in conjunction with a liquid transfer system when they are mounted inside the capsule.

Capsule sink temperature may be used in approaching the problem of temperature control for this case.

Considering sink temperature

$$\sigma T_w^{\,4} = \left(\frac{\alpha}{\epsilon}\right)\left(\frac{A_P}{A_T}\right) S + \frac{Q_g}{\epsilon_e A_T} \qquad (5)$$

it is evident that using a low value of $\frac{\alpha}{\epsilon}$ will minimize the effect of S upon T_w. Using a coating with a low value of α/ϵ (i.e., white paint with $\alpha = .2$ and $\epsilon = .9$) allows Q_g/ϵ_e to be "sized" to obtain the required T_w.

A. RTG Mounted Inside Capsule

1. Shield Temperature

Figure 8, derived from the analysis presented in Reference 1, shows that for $\alpha/\epsilon = .2$, $T_{S_{MAX.}}$ approaches 470°R as (kt/ϵ) approaches zero (i.e., as t approaches zero). Since the minimum shield temperature would be allowed to go no lower than -150°F (310°R), this means that with no shield liner the maximum gradient which could exist is 470 - 310 = 160°R. Hence, no shield liner is required.

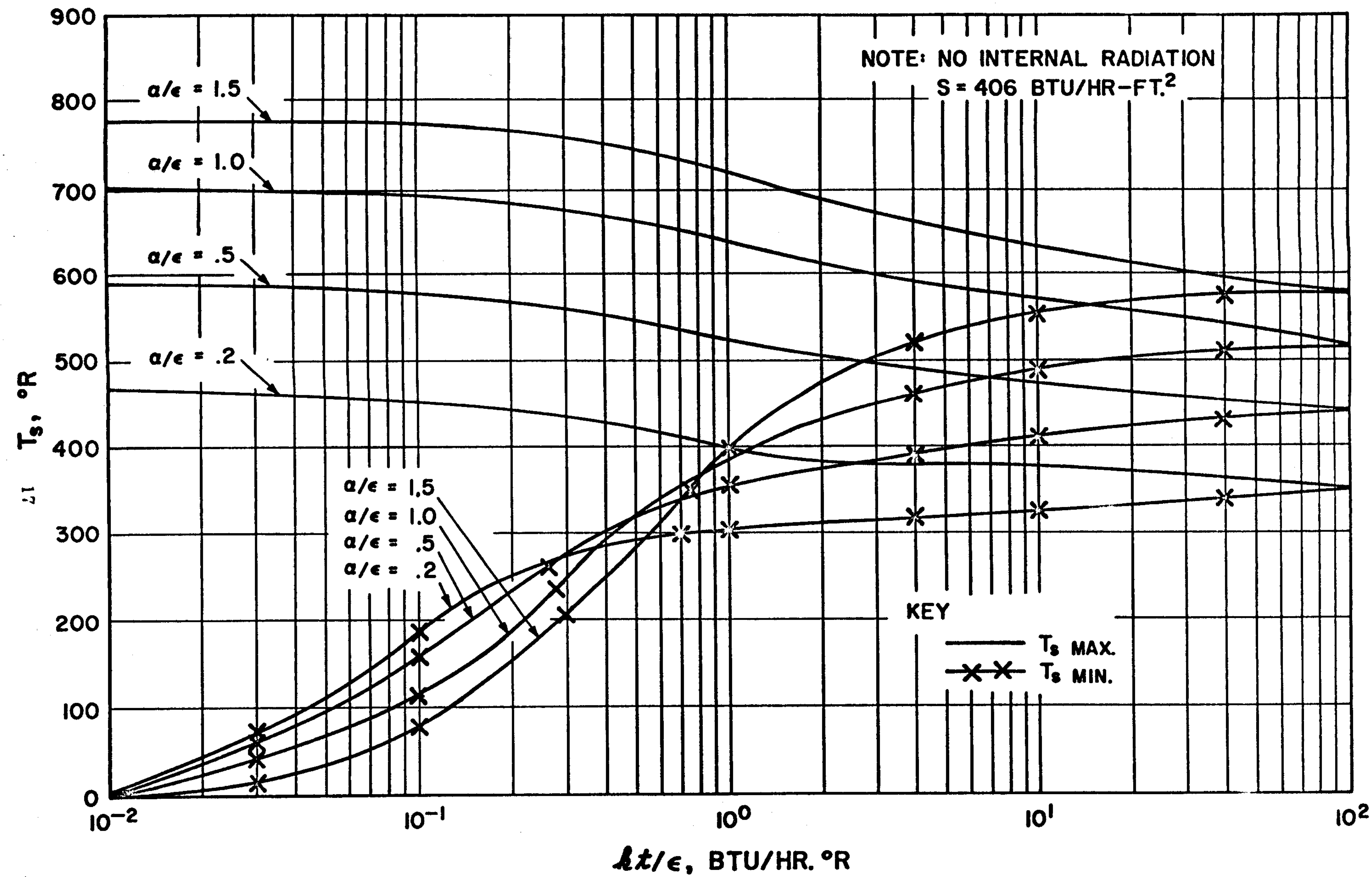

Figure 8. Shield Temperature Versus (kt/ϵ)

In order to prevent the shield temperature from falling below -150°F, it is necessary to insulate it. A fiberglas or a glass wool insulation could be used to accomplish this, but it is more advantageous, weightwise, to use a layer of foil around the outside of the shield. A nylon net would be used to prevent the foil from coming into contact with the shield in order to minimize the thermal conductance from the shield to space.

2. Capsule and RTG Temperatures

Figure 9 shows a cross-section through the vehicle. From a steady-state heat balance on the vehicle in the shade (assuming $\epsilon_f = .04$ and $\epsilon_{c_o} = .05$), it may be seen that:

Q_g (WATTS) (THERMAL PLUS ELECTRICAL)	TEMPERATURES WITH VEHICLE IN SHADE (i.e., S=0)			
	T_{C_o} (°F)	T_{C_i} (°F)	T_{RTG} (°F)	T_S (°F)
55	215	270	350	23
30	120	150	243	-43
25	93	118	190	-63
20	65	85	155	-85
18	52	70	140	-95
15	27	42	93	-110
10	-20	-12	50	-147

The capsule temperature (T_{C_i}) given above is for the case where the vehicle is in the shade of the bus with no solar flux incident upon it. The maximum and minimum capsule temperatures in the sun may be found from the following:

$$\sigma T_{C_i}^4 \text{ MAX.} = \left(\frac{\alpha}{\epsilon}\right)\left(\frac{A_P}{A_T}\right)_{\text{MAX.}} S_{\text{MAX.}} + \sigma T_{C_i}^4 \text{ (in shade)} \tag{6}$$

$$\sigma T_{C_i}^4 \text{MIN.} = \left(\frac{\alpha}{\epsilon}\right)\left(\frac{A_P}{A_T}\right)_{\text{MIN.}} S_{\text{MIN.}} + \sigma T_{C_i}^4 \text{ (in shade)} \tag{7}$$

where $\alpha = .2$

$\epsilon = .9$

$$\left(\frac{A_P}{A_T}\right)_{\text{MAX.}} = .26 \; ; \; \left(\frac{A_P}{A_T}\right)_{\text{MIN.}} = .23$$

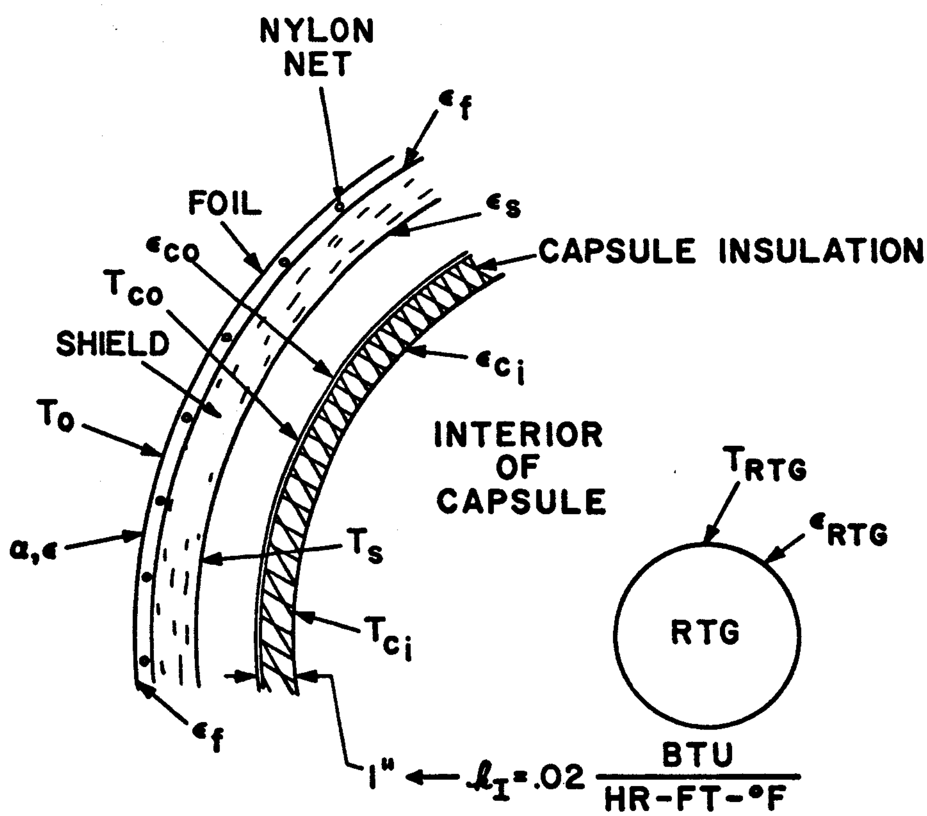

Figure 9. Section Through Vehicle

$S_{MAX.} = 406\ BTU/hr\text{-}ft^2$; $S_{MIN.} = 184\ BTU/hr\text{-}ft^2$

It may be found from this and the previous heat balance analysis that:

Q_g (WATTS) (THERMAL PLUS ELECTRICAL)	T_{C_i} (°F) (IN SHADE)	$T_{C_{i\,MAX.}}$ (°F) (IN SUN)	$T_{C_{i\,MIN.}}$ (°F) (IN SUN)	T_{RTG} (°F) (IN SHADE)	T_s (°F) (IN SHADE)
20	85	100	87	155	-85
19	78	98	85	147	-90
18	70	93	77	140	-95
17	60	83	67	125	-100
16	50	74	58	115	-105
15	42	67	50	93	-110

Hence, if between 15 and 20 watts are employed for temperature control, the capsule will change in temperature from a minimum of 42°F in the shade to 100°F in the sun at time of separation from the space bus. If the battery remains unactivated until after separation of the vehicle from the space bus occurs, then these temperature limits are acceptable; if the battery is activated before this, then between 16 and 20 watts will be required.

B. RTG Mounted Outside Vehicle

This type of temperature control system would employ an RTG unit mounted outside the vehicle. The electrical output from this RTG would be dissipated in heaters inside the capsule which, in turn, would maintain the capsule temperature. If the electrical output were used for communication, a great percent of it would be dissipated directly in the electronic equipment, thereby maintaining its temperature. Separation of the RTG from the vehicle prior to entry at Mars would be necessary and could be attained by the use of an explosive bolt type of device.

A. Shield Temperature

The analysis made for the case of the internally mounted RTG applies here also. Hence, no shield liner is required for minimizing the thermal gradient around the shield.

B. Capsule and RTG Temperatures

Again, as in the case of the internally mounted RTG, a steady-state heat balance may be investigated. This will result in the following possible design points:

Q_g (WATTS) (THERMAL PLUS ELECTRICAL)	T_{C_i} (°F) (IN SHADE)	$T_{C_{i\,MAX.}}$ (°F) (IN SUN)	$T_{C_{i\,MIN.}}$ (°F) (IN SUN)	T_s (°F) (IN SHADE)
20	85	100	87	-85
19	78	98	85	-90
18	70	93	77	-95
17	60	83	67	-100
16	50	74	58	-105
15	42	67	50	-110
14	30	56	40	-118
13	17	43	27	-125
12	8	38	20	-132

As before, it is evident that between 15 and 20 watts may be used for temperature control.

It should be noted that in the analysis of steady-state heat balance employed for the cases of RTG mounted inside the capsule and outside the vehicle, no variation (with view angle) in the emissivity across the foil was assumed. At present, a single foil has not been tested to see if such a variation does indeed exist as it does for multiple foils (i.e., superinsulation). Since the amount of heat necessary to control the capsule temperature is quite dependent upon effective (or overall) emissivity, a modulated form of heat generation would be more desirable than a constant heat output. Such a modulated device could be obtained by using the RTG mounted outside the vehicle as described above.

VI. Temperature Control System Weights

Figure 10 presents the summary of weights for the various temperature control systems. It is assumed that scaling down the RTG unit to 19 thermal watts scales the electrical output down to .95 watts.

It may be seen that the system utilizing the RTG unit mounted internal to the capsule is the lowest in weight. While the system employing the externally mounted RTG unit weighs more than any other system, it produces a quantity of electrical power equal to 15 watts. This weight must, then, be considered in conjunction with the weight required for the power supply of the vehicle and also the reliability of same.

CONCLUSIONS:

The principal conclusion to be made in this paper is that in order to select a temperature control system for a Mars probe, several systems should be considered and compared.

The analyses presented here for the four types of temperature control system should not be considered to be all-inclusive. These analyses are preliminary and could be subject to change. However, based on this preliminary investigation, the RTG type of system appears to be quite desirable. Tests have shown the RTG units to be very rugged and reliable. In addition, the electrical power output from these units is affected only slightly by a variation of solar flux incident upon them (as is the case of the externally mounted unit).

COMPONENT	SYSTEM WEIGHT				
				RADIOISOTOPE SYSTEMS	
	α/ϵ COATING SYSTEM	α/ϵ CONTROL SYSTEM	SUPER-INSULATION SYSTEM	RTG INSIDE CAPSULE (.95 ELECTRICAL WATTS)	RTG OUTSIDE VEHICLE (15 ELECTRICAL WATTS)
Magnesium Liner or Shell	4.7 lb.	5.0 lb.	-	-	-
Solar Cells	.7	-	1.6 lb.	-	-
α/ϵ Shutters and Tubing	-	8.0	-	-	-
Battery Insulation	.7	.7	.7	.7 lb.	.7 lb.
Heat of Fusion Material	6.5	-	-	-	-
Superinsulation Shell	-	-	9.8	-	-
RTG Unit	-	-	-	4.5	20.6
Foil and Nylon Net	-	-	-	3.0	3.0
Capsule Insulation	3.0	3.0	3.0	3.0	3.0
RTG Separation Device	-	-	-	-	5.0
Superinsulation or Clam-Shell Removal Device	-	5.0	5.0	-	-
Total	15.6	21.7	20.1	11.2	*32.3

*Assumes no heaters necessary (heat is dissipated in electronic equipment).

Figure 10. Thermal Control System Weights

NOMENCLATURE

A_P	=	projected area of vehicle (a function of view angle) - ft.^{2}
A_T	=	total surface area of vehicle - ft.^{2}
α	=	solar absorptivity - dimensionless
α_e	=	effective solar absorptivity (between capsule and sink) - dimensionless
C_p	=	specific heat of vehicle - $\frac{\text{BTU}}{\text{lbm - }^{\circ}\text{F}}$
ϵ	=	emissivity - dimensionless
ϵ_e	=	effective emissivity (between capsule and sink) - dimensionless
$\mathcal{F}$	=	radiation configuration factor - dimensionless
k	=	thermal conductivity - BTU/hr-ft-$^{\circ}$F
Q_g	=	internal heat generation - watts; BTU/hr.
σ	=	Stefan-Boltzmann constant = $.1713 \times 10^{-8}$ BTU/ft^2-hr-$^{\circ}$R^4
S	=	solar flux per unit area - BTU/hr-ft.^{2}
t	=	shield liner thickness - ft.
T	=	temperature - $^{\circ}$R; $^{\circ}$F
w	=	weight of vehicle - lbm.
θ	=	time - hr.; or view angle - degrees

SUBSCRIPTS

B	=	battery; back (aft) end of vehicle
C	=	capsule
e	=	effective
H	=	holes in insulation or attachment points to vehicle
i	=	initial, interior
MIN.	=	minimum

SUBSCRIPTS (Cont'd)

MAX. = maximum

P = projected

S = shield

S_i = inside of shield

S_o = outside of shield

T = total

W = sink (environment)

REFERENCES

1. Tatom, John W.; Shell Radiation; A.S.M.E., Paper number 60-WA-234

2. Eckert and Drake; Heat and Mass Transfer; Second Edition; McGraw-Hill Book Co., Inc.

3. Baker, Joel K.; Temperature Control Techniques for Solar Energy Converters; ASD Technical Report 61-689; Dec. 1961